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Guided and Leaking Interface Waves for NDI/NDE

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Guided and Leaking Interface Waves for NDI/NDE

Abstract

Last year at this review one of us pointed out that it was theoretically possible to propagate guided elastic waves along the interface between an installed interference-fit fastener and the parts that it joins, and that these waves might be useful for nondestructive inspection and evaluationl. During discussion of that paper, the speaker was asked if experiments were planned, and another questioner wanted to know what would happen if elastic parameters of fastener and part didn't fall in the comparatively narrow ranges for which unattenuated guided waves can propagate.

The speaker replied that experiments were indeed planned, and that, hopefully, even when material parameters did not allow guided waves, attenuated interface waves might still propagate and be useful for inspection and evaluation.

This report can be viewed as an amplified answer to the two questions. We have carried out experiments. They confirm the existence of both true guided waves, and of "leaking" or attenuated waves, on interfaces between materials of engineering interest. The theory presented last year, with some extensions, is a useful guide to excitation and reception methods, propagation speeds, and for leaking modes, attenuation factors. Preliminary pulse-echo observations indicate that these waves can be used for indications of flaws in awkward places, such as on a fastener hole in an inner plate.

Disciplines

Materials Science and Engineering | Structures and Materials

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GUIDED AND LEAKING INTERFACE WAVES FOR NDI/NDE

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Introduction

Last year at this review one of us pointed out that it was theoretically possible to propagate guided elastic waves along the interface between an installed interference-fit fastener and the parts that it joins, and that these waves might be useful for nondestructive inspection and evaluation[1]. During discussion of that paper, the speaker was asked if experiments were planned, and another questioner wanted to know what would happen if elastic parameters of fastener and part didn't fall in the comparatively narrow ranges for which unattenuated guided waves can propagate.

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Theory

Guided elastic waves on a plane interface between dissimilar materials were first treated by Stoneley[2]. They are characterized by the dispersion relation

$$\begin{aligned} & c^4[(\rho_1-\rho_2)^2 - (\rho_1A_2+\rho_2A_1)(\rho_1B_2+\rho_2B_1)] \\ & + 2Kc^2[\rho_1A_2B_2 - \rho_2A_1B_1 - \rho_1 + \rho_2] \qquad (1) \\ & + K^2(A_1B_1 - 1)(A_2B_2 - 1) = 0, \end{aligned}$$

which is known as the Stoneley equation[3]. In (1):

ρ_i = density in i^{th} material

c = wave speed

$$A_i = 1-c^2/a_i^2, \quad B_i = 1-c^2/b_i^2, \quad K = 2\ (\rho_1 b_1^2 - \rho_2 b_2^2),$$

where

a_i = dilatation wave speed in i^{th} material

b_i = shear wave speed in i^{th} material.

As shown in Reference 1, axially symmetric guided interface waves can propagate on a cylindrical interface between different materials. These waves are described by the dispersion relation shown on the next page. Here K is the wave number, and $\xi \equiv kR$, where R is the radius of the interface. Equation (2) reduces to Eq. (1) as $|\xi| \to \infty$, i.e., as the wavelength becomes very small compared to the interface's radius. Thus Eq. (1) serves as a useful "pilot" for finding solutions of Eq. (2).

Now, for some materials, Eqns. (1) and (2) have solutions for which c, k, A_i, B_i are all real quantities. These roots correspond to waves whose amplitudes decrease exponentially away from the interface, and whose amplitudes do not change along the interface. These are true guided waves, some examples of which, in cylindrical geometry, were given in Reference 1. As pointed out in Reference 3 while guided modes may not exist for some other materials, there may in these cases, be solutions of Eqs. (1) and (2) for which c, k, A_i, and B_i are complex. In some cases these roots correspond to waves whose amplitudes decay along the interface and to one side of the interface, but not to the other side of the interface. These solutions may be interpreted as "leaking" or pseudo-guided" waves propagating along the interface.

Measurements of wave speeds and densities for representative steel and aluminum materials showed that an interface between these metals would not support classical guided waves. The interface would, however, support leaking interface waves. The displacement field of a leaking interface wave on a plane Al/Fe interface is shown in Fig. 1.

In the denser materials, this displacement field resembles that of a Rayleigh wave. Displacements in the lighter material do not at all resemble Rayleigh wave displacements.

This displacement field is composed of four functions, three of which have amplitudes which decay exponentially away from the interface, and one which represents shear wave energy leaking away at a rather shallow angle to the surface. The leaked shear waves are undamped along their rays. However, stations farther and farther from the interface along a line perpendicular to the interface intercept leaked shear energy which originates farther and farther back up the interface, and so comes from regions of greater wave amplitude. For this reason displacement field amplitudes increase exponentially with increasing distance from the interface in the ligher material, as

$$\begin{bmatrix} 2\rho_1 b_1^2 A_1 K_1(A_1\xi) & 2\rho_2 b_2^2 A_2 I_1(A_2\xi) & \rho_1 b_1^2(2-c^2/b_1^2)K_1(B_1\xi) & \rho_2 b_2^2(2-c^2/b_2^2)I_1(B_2\xi) \\ \rho_1\left\{(c^2-2b_1^2)K_0(A_1\xi) - \frac{2b_1^2A_1}{\xi} K_1(A_1\xi)\right\} & -\rho_2\left\{(c^2-2b_2^2)I_0(A_2\xi) + \frac{2b_2^2A_2}{\xi} I_1(A_2\xi)\right\} & -2\rho_1 b_1^2 B_1\left[K_0(B_1\xi) + \frac{1}{B_1\xi} K_1(B_1\xi)\right] & 2\rho_2 b_2^2 B_2\left[I_0(B_2\xi) - \frac{I_1(B_2\xi)}{B_2\xi}\right] \\ K_0(A_1\xi) & -I_0(A_2\xi) & B_1K_0(B_1\xi) & -B_2I_0(B_2\xi) \\ A_1K_1(A_1\xi) & A_2I_1(A_2\xi) & K_1(B_1\xi) & I_1(B_2\xi) \end{bmatrix} \begin{bmatrix} \alpha \\ \gamma \\ i\beta \\ -i\delta \end{bmatrix} = 0 \qquad \text{Eq. (2)}$$

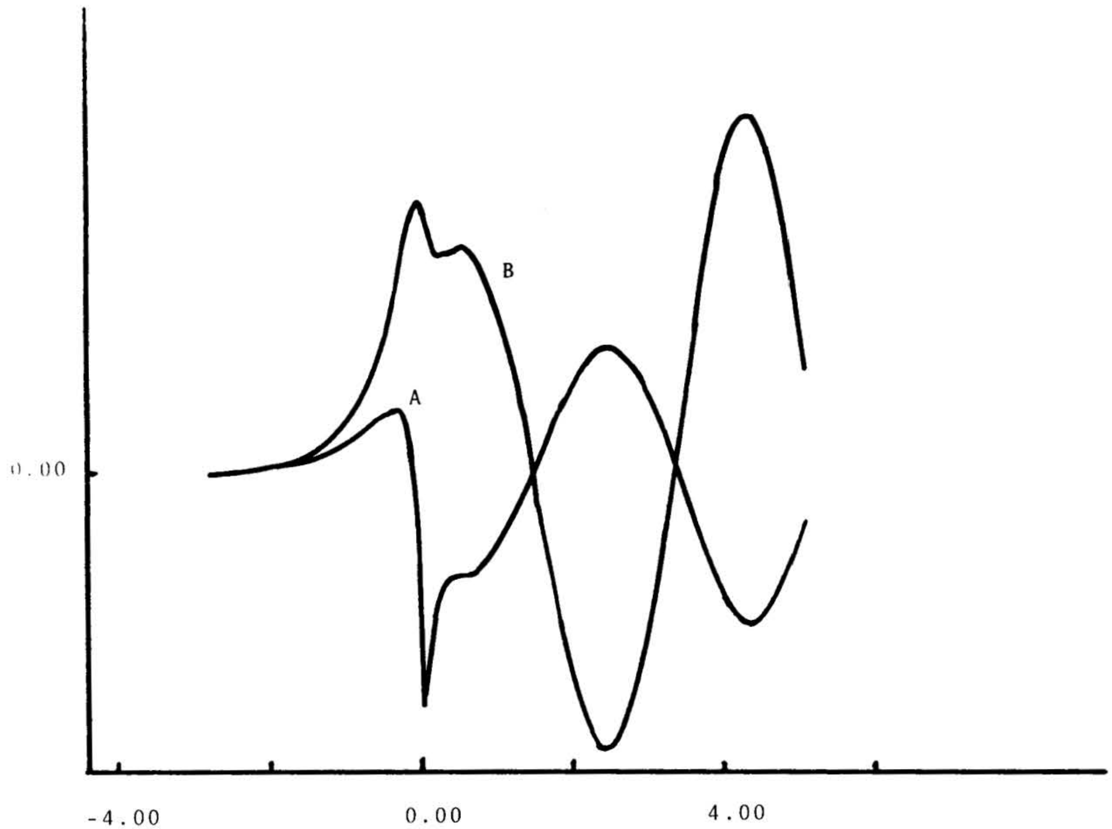

Fig. 1. Displacement field components (arbitrary units) parallel to interface (A) and perpendicular to interface (B), versus distance from interface (cm.).

indicated in Fig. 1. Wave speeds for some interfaces of engineering interest are collected in Table I.

Experiments to Identify Waves

Our first experiments to test the theoretical predictions of leaking interface waves compared observed wave speeds and damping factors with predicted ones. The displacement field of Fig. 1 suggests that mode conversion from Rayleigh waves in the denser material to interface waves may be efficient, since the interface wave's displacement field is similar to that of a Rayleigh wave in the denser material, while mode conversion from Rayleigh waves in the ligher material is not likely to be efficient, since the displacement field of the leaking interface wave in the ligher material is very unlike the Rayleigh wave displacement field. For this reason, we decided to determine wave speeds with the apparatus of Fig. 2.

A block of the lighter material rests on a somewhat larger plate of denser material, with surface wave transducers arranged to put surface wave energy into and out of the denser material. It turned out to be necessary to load the system rather heavily to get rid of irregularities in the two surfaces and produce a true interface. On this account the experiments were conducted in a press.

Results of this experiment, performed for Ti/Al and Fe/Al systems and for two sizes of aluminum blocks, are shown in Fig. 3. This figure shows time shifts between Rayleigh speed in the denser material, observed at zero load on the aluminum block, plotted against loading of the aluminum block. Reasonable quantitative agreement between predicted time shifts, and shifts observed for interface loadings greater than about 2.5×10^4 psi, seems to have been obtained. However, first results of the same experiments with the same blocks, but at 10 MHz frequency, gave much poorer agreement.

It seemed possible that surface irregularities were responsible for the "dispersion" observed. To test this, the blocks were polished with 3 μm diamond paste, and the experiments repeated. Results are shown in Fig. 4. Improving surface condition did, indeed, restore good agreement between predictions and observations.

Another check on identification of interface waves is given by attenuation. Figure 5 shows comparisons between observed and predicted attenuations for polished Al/Fe interfaces at two frequencies. The agreement is encouraging.

To provide further documentation of the dependence of interface wave speed on surface quality, the experiments were repeated again, using aluminum blocks roughened with 60 grit paper. As shown in Fig. 6, for each loading of the interface, the roughened block gave a much smaller time shift than the predicted one, and the discrepancy was greater at the higher frequency. Attenuations for the roughened surfaces, shown in Fig. 7, appear to be fairly complicated functions of interface loading, for which we have no theoretical explanation now. Further work in this area might, we believe, lead to methods for evaluating surface quality.

Table I.

Material	Dilatation Wave Speed cm/s x 10^5 (measured)	Shear Wave Speed cm/s x 10^5 (measured)	Density g/cm^3 (measured)	Rayleigh Wave Speed cm/s x 10^5 (predicted)	Interface Wave Speed cm/s x 10^5 (predicted)
Al	6.31	3.10	2.77	-	-
Fe	5.89	3.21	7.86	2.9713	-
Ti	6.11	3.27	4.44	3.0323	-
Al/Fe	-	-	-	-	3.1483 - 0.00724i
Al/Ti	-	-	-	-	3.2545 - 0.02500i
Al/Fe Cylinder, 0.85 in. radius, $\omega = 6.28 \times 10^7 s^{-1}$	-	-	-	-	3.1322 - 0.00768i

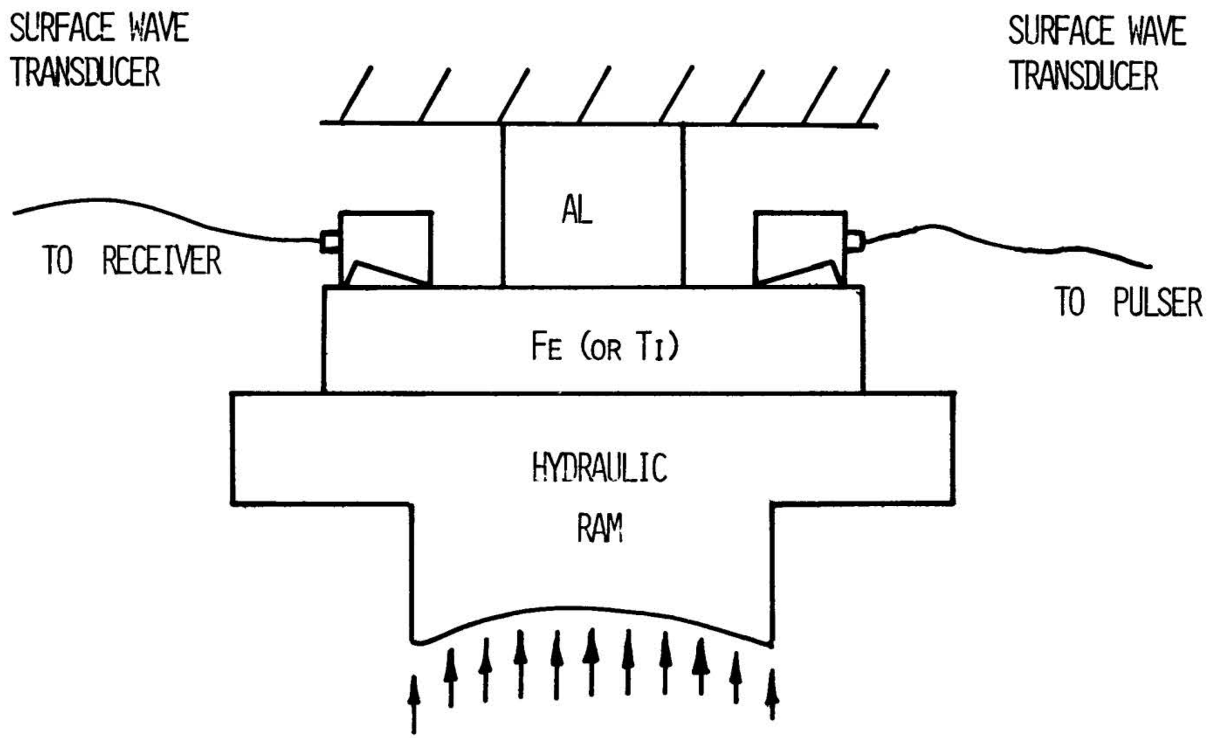

Fig. 2. Experimental arrangement for determining wave velocities.

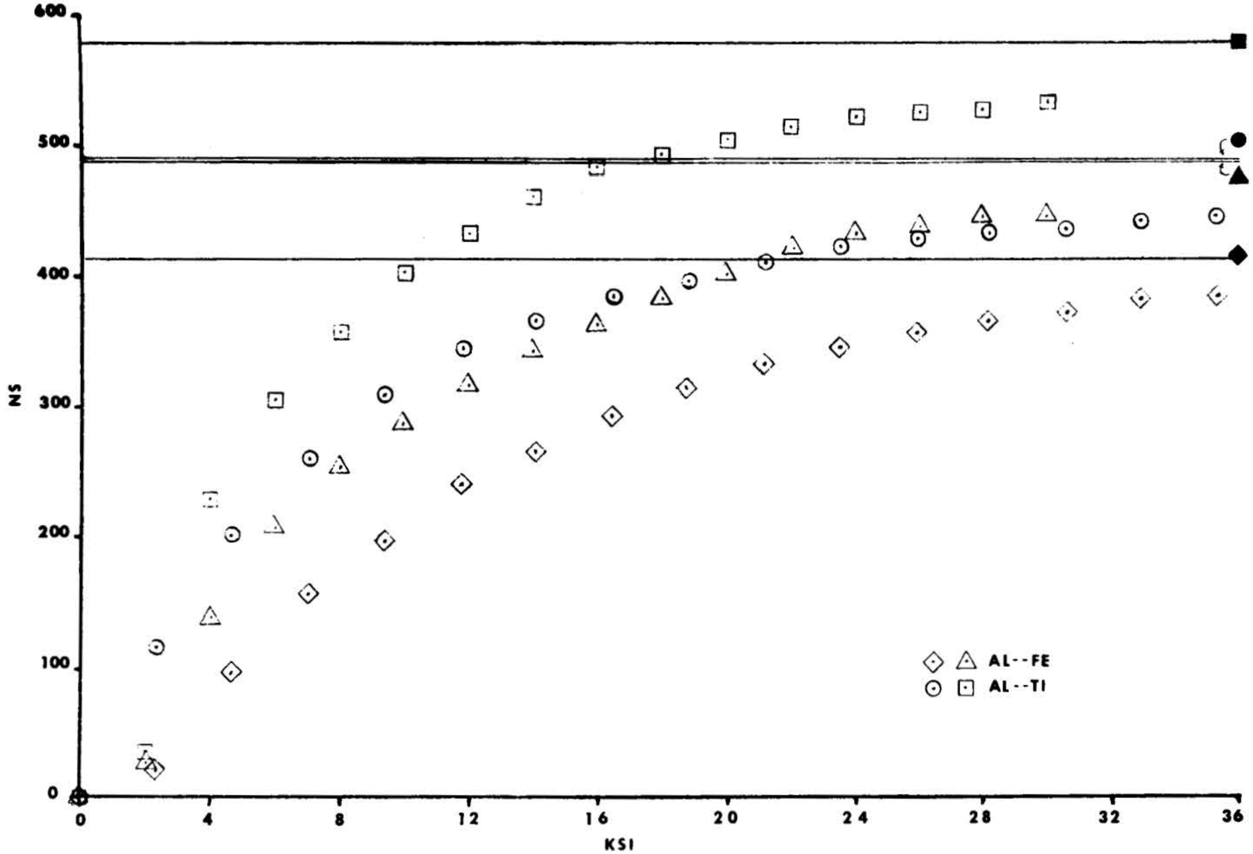

Fig. 3. Time shifts of Rayleigh waves for Ti/Al and Fe/Al systems as a function of loading.

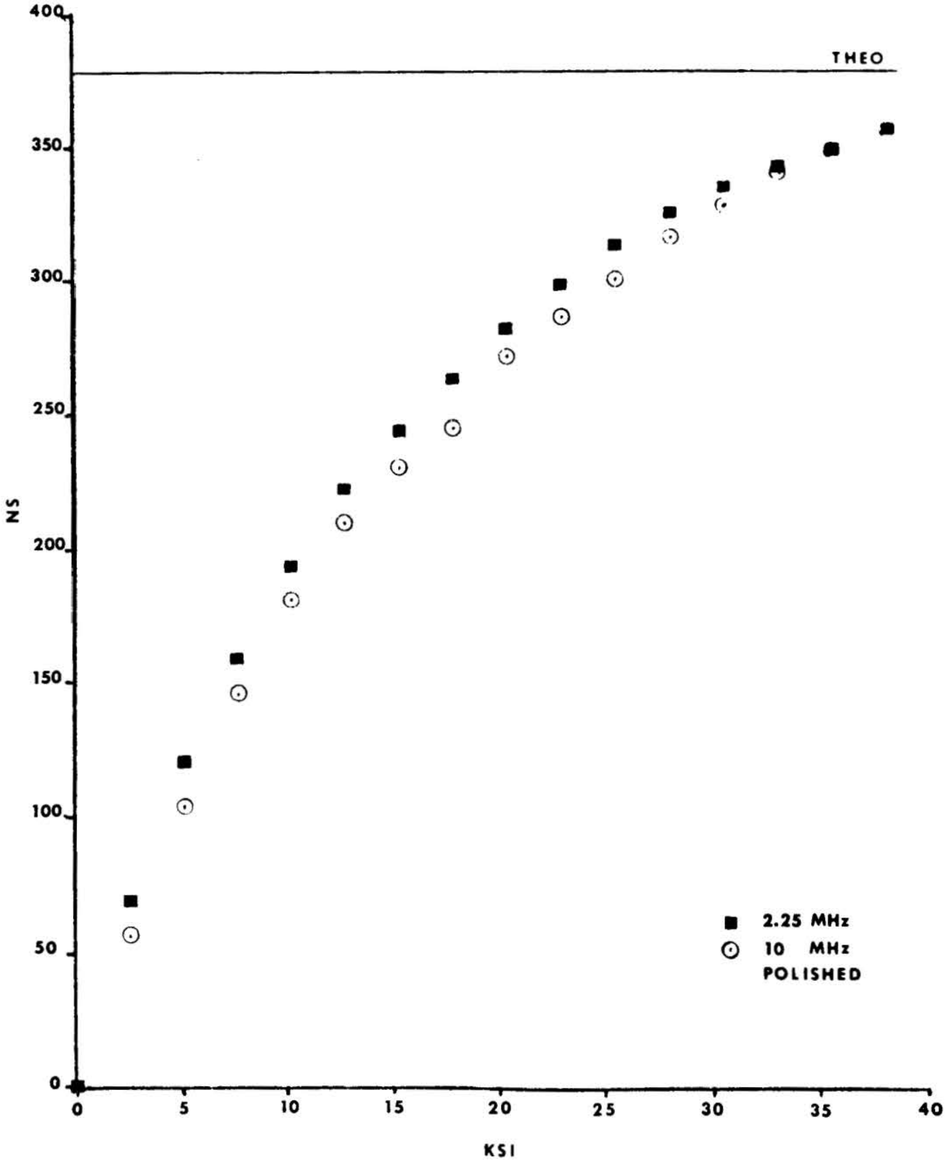

Fig. 4. Time shifts for polished blocks at 2.25 and 10 MHz.

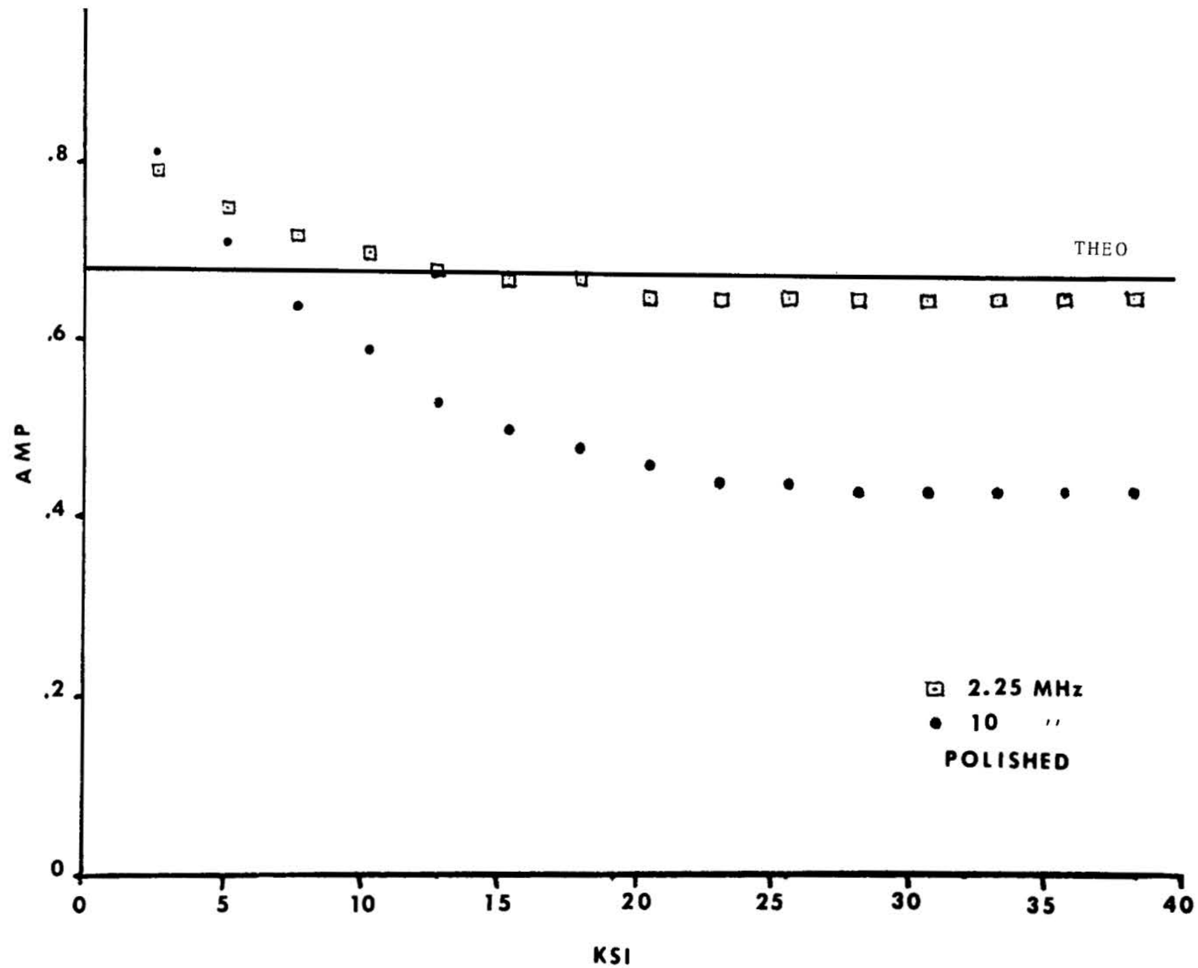

Fig. 5. Experimental and theoretical attenuations for a Fe/Al interface at 2.25 and 10 MHz.

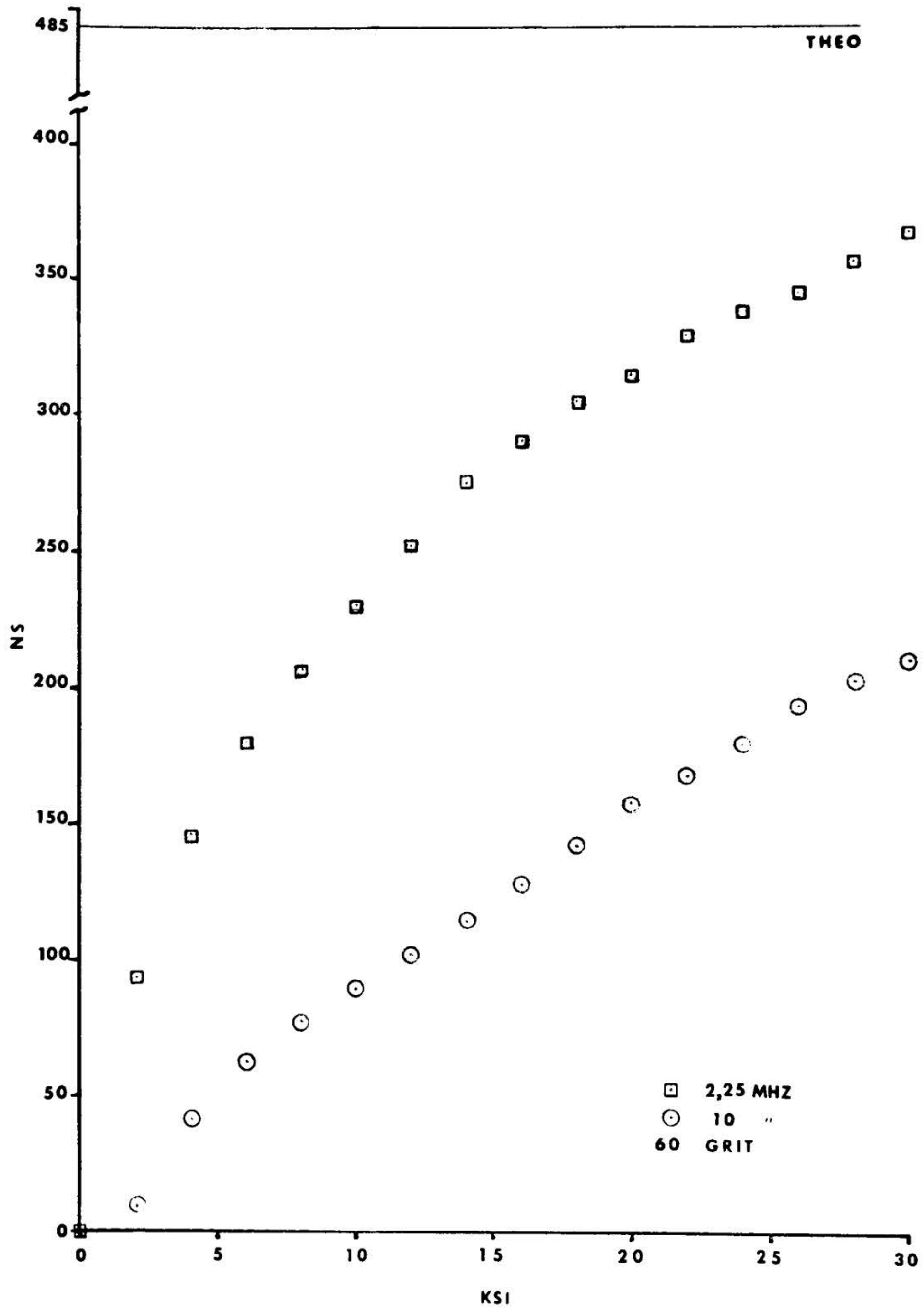

Fig. 6. Time shifts for roughened aluminum blocks.

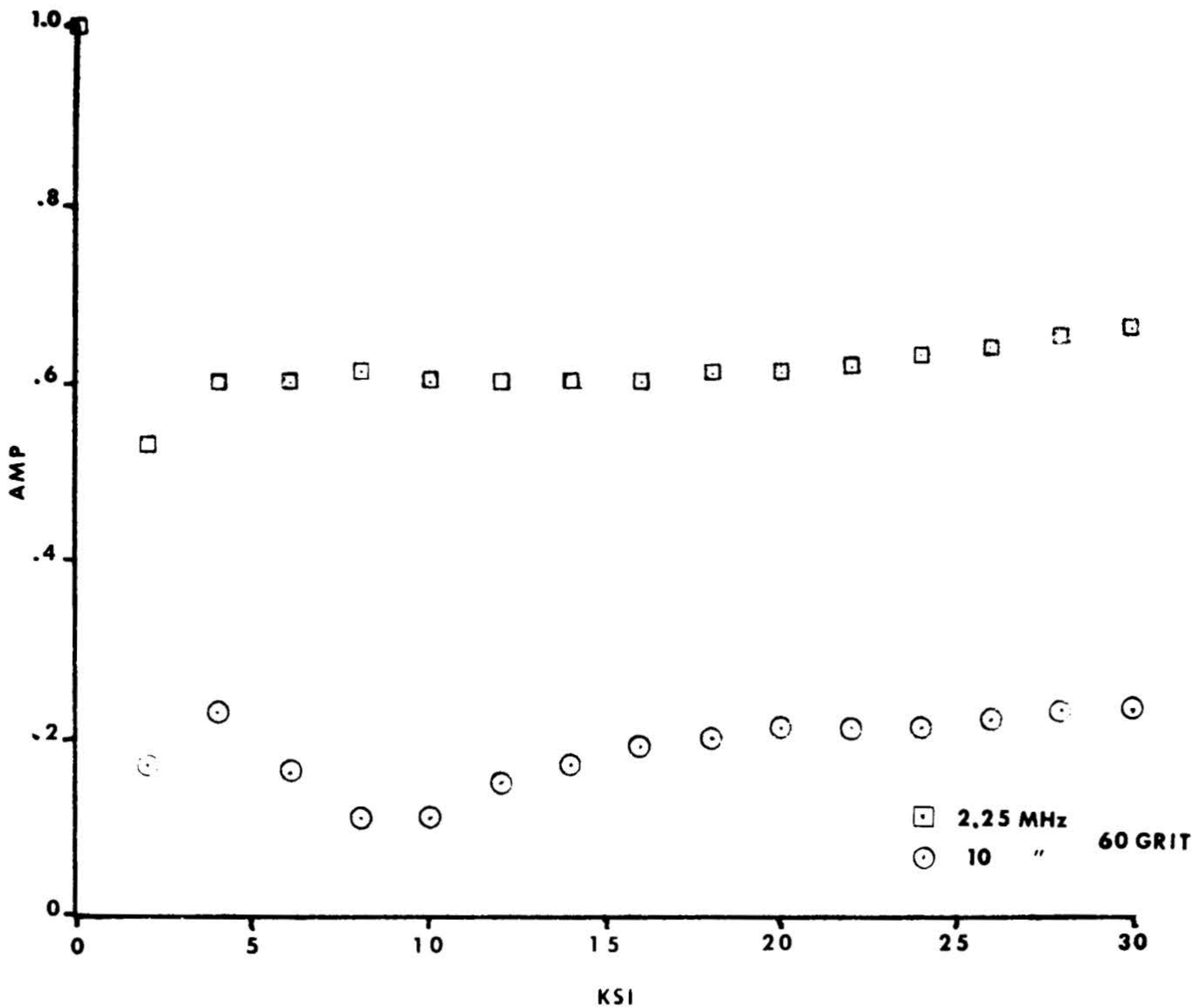

Fig. 7. Attenuation for roughened aluminum blocks.

The apparatus of Fig. 8 was used for experiments to identify cylindrically symmetric interface waves. It was determined experimentally that cylindrically symmetric surface waves could be excited reproducibly on a tapered steel pin, by a PZT-4 piezoelectric transducer blank attached to one end. These waves were received by a surface wave wedge transducer, mounted as shown in Fig. 8 so that it could be rotated to different azimuthal stations around the surface of the cylinder. Cylindrical symmetry of both surface waves and interface waves was confirmed by observations at several azimuthal stations.

Time histories of pitch-catch experiments with the pin in and out of a tapered hole in an aluminum block were taken. The observed time shift in this experiment, done at 10 MHz, was 302 nanoseconds. The predicted time shift is 389 nanoseconds. However, since surface quality of pin and hole were not clearly so good as that required for good agreement between theory and experiment in the plane case, we felt the result gave reasonable preliminary confirmation of the theory for cylindrically symmetric waves.

Flaw-Detection Experiments

To give preliminary indications of the usefulness of interface waves for flaw detection, pulse-echo experiments were performed, both with the apparatus of Fig. 2 and with a modication of the apparatus of Fig. 8, using both flawed and unflawed aluminum blocks in the former and using flawed and unflawed plates and sandwiches of plates in the latter. Figure 9 shows oscilloscope traces from the block-plate experiments. The upper three pictures, from left to right, are time histories for an unflawed block, at no load, four tons, and twenty tons load. At no loading on the block, the trace shows only the reflection of a surface wave from the two closest corners of the steel block. With four tons and wtih twenty tons applied to the aluminum block, there is a return from the front and from the back of the aluminum block, and returns from the two corners of the steel block are still visible. This result is encouraging, for two reasons. First, the front and back edges of the aluminum block are discontinuities in the interference fit fastener installation in which the fastener does not contact an inner plate at all; one would hope at least to "see" these with interface waves, and the figure indicates he may. Second, one would like to use interface waves to get energy into and out of interior parts, and the persistence of the echoes from the corners of the block indicates that this is indeed possible.

The bottom traces show time histories of the pulse-echo experiment using an aluminum block with a rather generous flaw, 0.060 inch in width, 0.130 inch in depth, located in the center of the block. Again, loadings were zero, four tons, and twenty tons. Returns from the flaw are, as one would hope, clearly visible. Also, sufficient energy "gets through" the flawed region that returns from the corners of the steel block are still apparent.

Turning to the cylindrical case, the apparatus of Fig. 8 was modified to use only the surface wave transducer in a pulse-echo mode, sending and receiving along a generator of the pin's cylindrical surface. A tapered hole

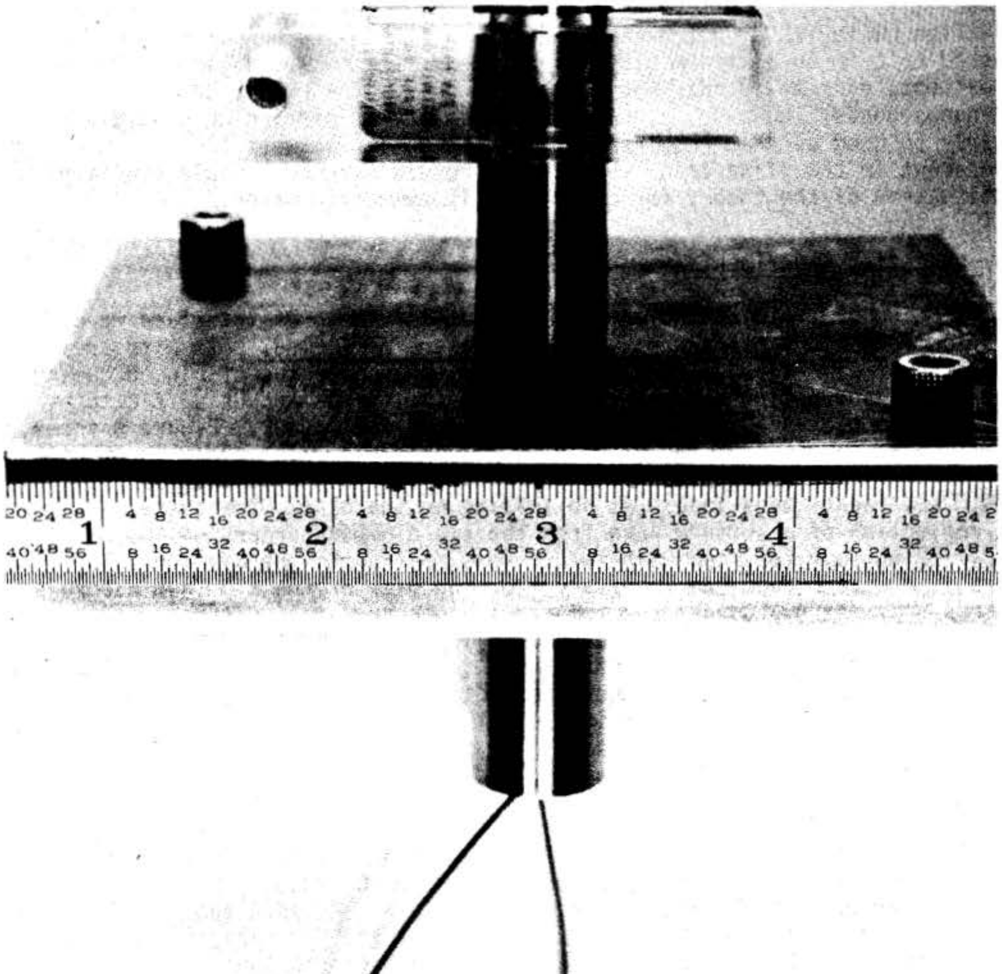

Fig. 8. Apparatus for characterizing interface waves.

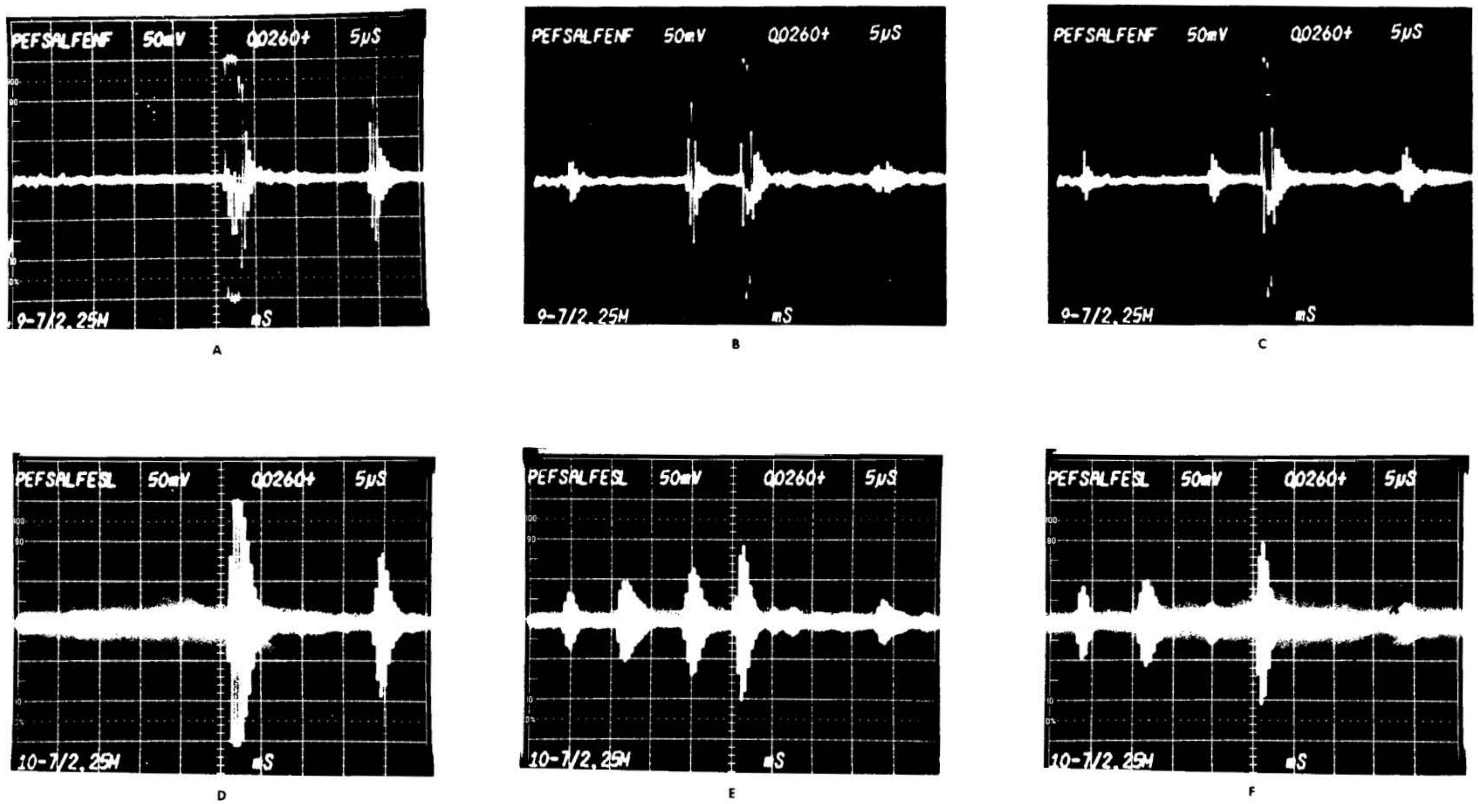

Fig. 9. Oscilloscope tracers for block-plate experiments. Top curves are time histories for an unflawed block (a) at no load, (b) at 4 tons load, and (c) at 20 tons load. The bottom curves are time histories for a flawed Al block (a) at no load, (b) at 4 tons load, and (c) at 20 tons load.

was bored into a stack of two aluminum plates, one 0.375 inch and the other 0.500 inch in thickness. The upper traces in Fig. 10 show pulse-echo results with the pin installed in only the thinner plate. Echoes from front and back faces of the plate are clearly visible. The two traces were taken at different azimuthal stations, to demonstrate the cylindrical symmetry of the pin installed in the thinner plate. The lower traces of Fig. 10 show pulse-echo results from the pin installed only in the thicker plate. The left trace show returns along a certain generator of the pin, for which there was not a pronounced return from the front surface of the thicker plate. We conjecture that there is a flaw on pin or block at that azimuthal station which acts as an impedance match, generating only a small echo while allowing energy to enter the back plate, so that a pronounced return is seen from the rear surface of the back plate. The right trace, taken at yet another azimuthal station, shows straightforward echoes similar to those of the upper traces.

Finally, Fig. 11 shows time histories of echoes when the pin is installed in flawed (lower traces) stacks of two plates. For the unflawed stack, returns from the front and back edges of the stack are quite clear, as is a return from the faying surface. The flaw, shown in Fig. 12 is gross: it is a roughly triangular gouge, commencing on the back edge of the rear plate. It is 0.160 inch wide at its base on the edge of the plate, tapering to a point about 0.380 inch from the base. The flaw's depth is roughly .020 inch.

The first of the lower traces on Fig. 11 shows pulse-echo results for propagation along the generator of the pin's surface which encounters the vertex of the flaw, point A in Fig. 12. One sees returns from the front of the front plate and from the faying surface, but not from the back surface, which, of course, is not present on this generator. The second trace, taken on a generator which does not pass through the flaw, shows again the returns from front surface, faying surface, and back surface. These results show, we feel, that interface waves will give indications of at least grossly flawed installations of interference-fit fasteners.

Conclusions

We think the material of this report documents sufficiently good agreement between theoretical predictions and observations of leaking interface waves in materials of engineeering interest to support further explorations of applications of these waves. The preliminary experiments on flaw detection and surface quality determination indicate that interface waves may have useful applications as tools in nondestructive inspection and evaluation.

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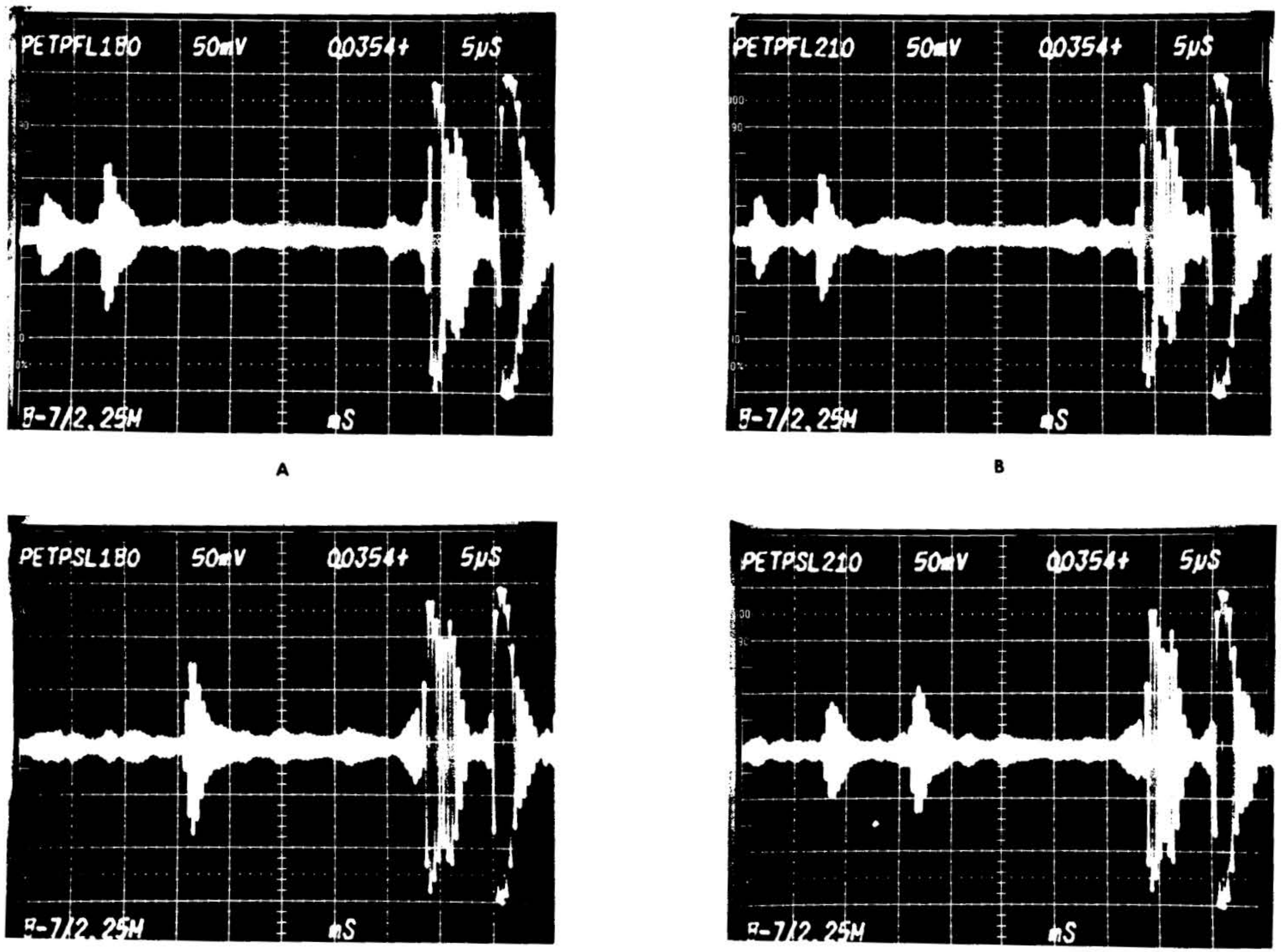

C

D

Fig. 10. Pulse-echo data for a 0.375 and a 0.500 thick Al plate with holes. Pin is inserted in 0.375 inch plate in (a) and (b); in 0.500 inch plate in (c) and (d).

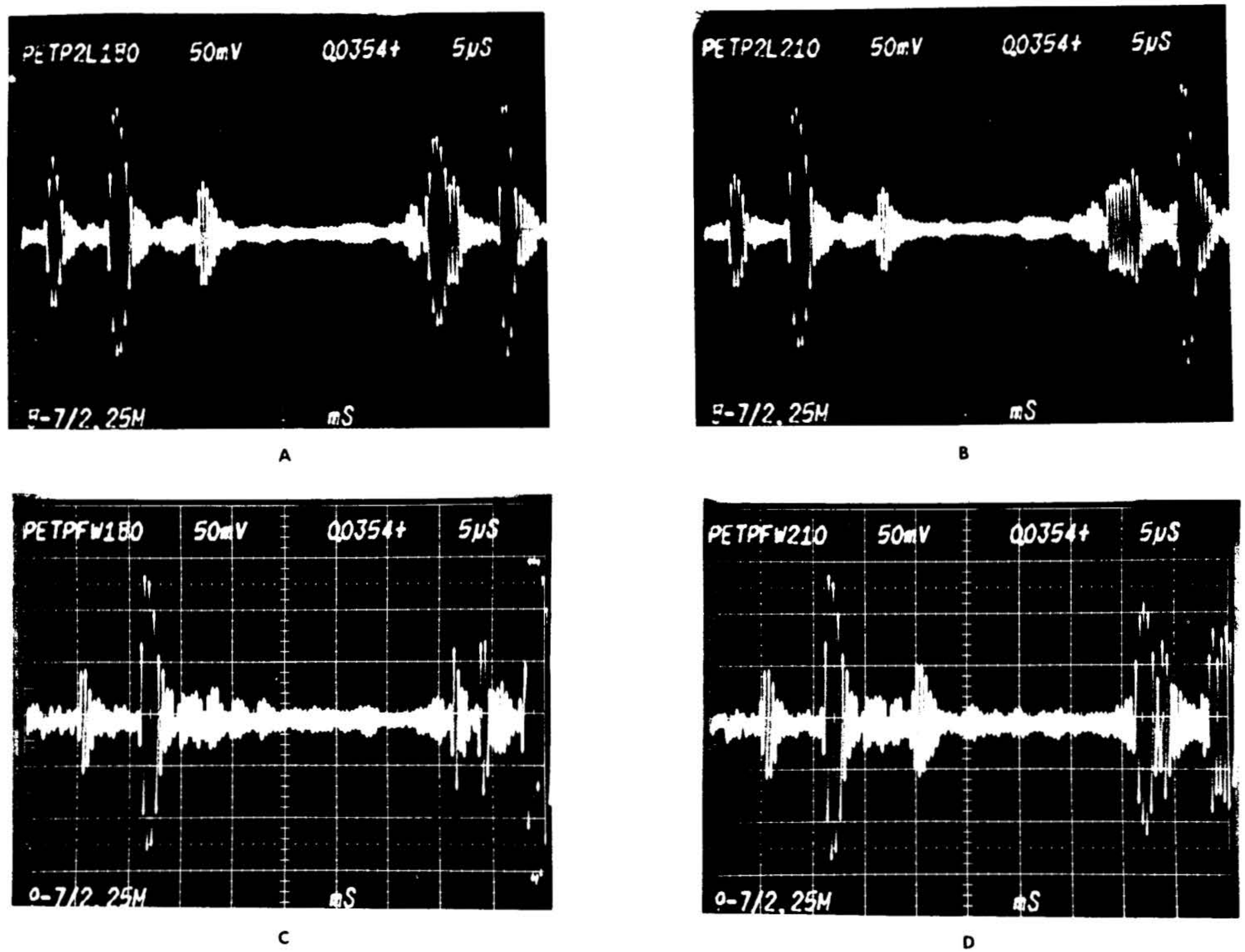

Fig. 11. Pulse-echo data for unflawed plates (a) and (b); and for flawed plates (c) and (d).

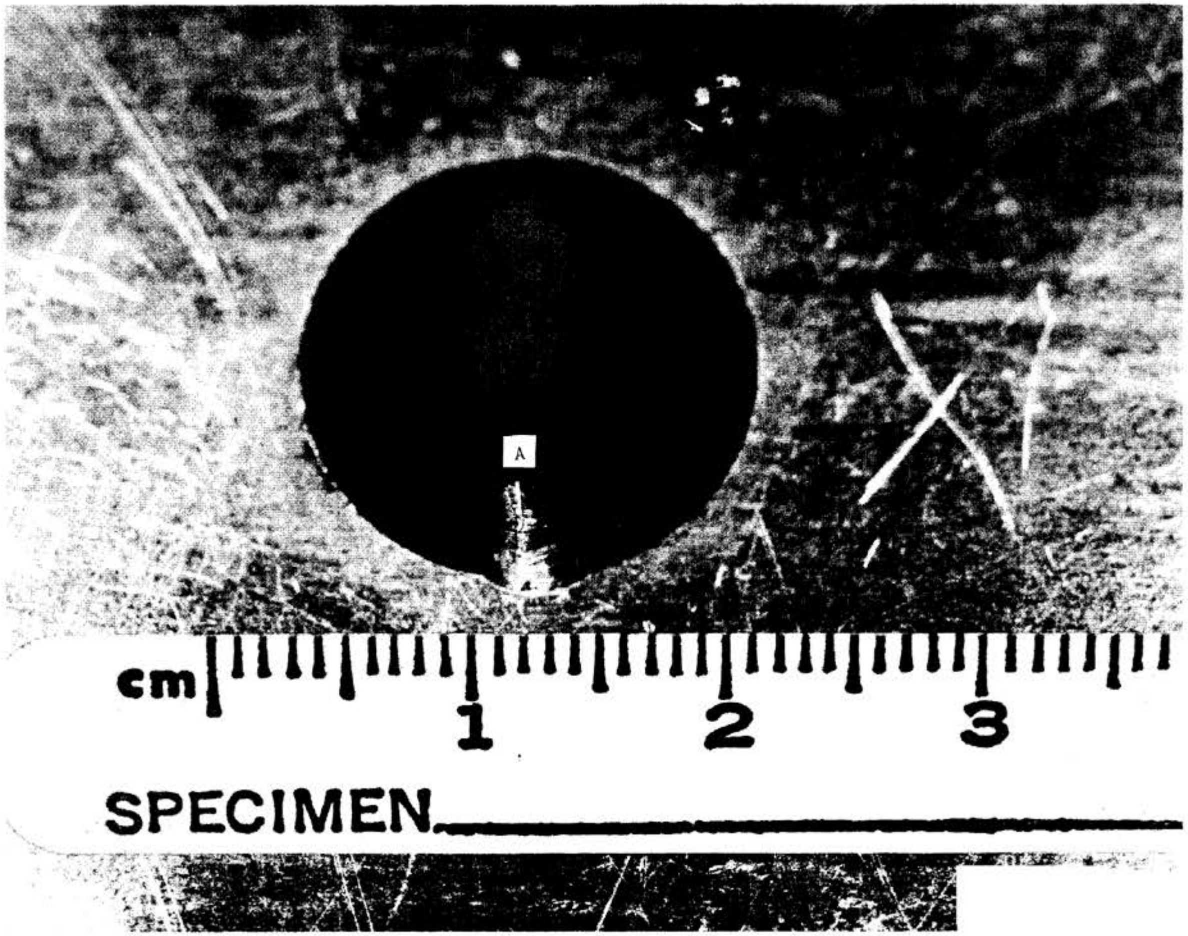

Fig. 12. Photograph of flaw in hole in Al plate.

DISCUSSION

DR. BRUCE THOMPSON: The floor is open for questions.

MR. STEVE HART (NRL, Washington): How are these flaws oriented relative to your direction of propagation? I don't think I caught that.

DR. LEE: I don't think I made it very clear. Now, if we look into the hole in the back plate of the aluminum there is a gouge, a rather irregular shape. If we look in the other way, we see a hole in a plate with a defect. The situation for which there was no return from the back end corresponded to propagation down that generator of the cylinder that went through the apex of this flaw. Then turn it over about to here and, sure enough, you get back to seeing something.

DR. HENRY BERTONI (Polytechnical Institute of New York): When you had the two aluminum plates in contact, was there a time delay when there was no pressure on them equal to that for just the Rayleigh wave on the end?

DR. LEE: Yes. It would be difficult but--

DR. BERTONI: I have another question that is unrelated. The other question is: can you estimate if there is a correlation between the amount of time delay and, say, the fraction of the areas of the aluminum and steel that are in contact?

DR. LEE: Yes. In fact, I didn't want to put them up, but it's a little hard to get very good blocks. That is apparently something of a challenge for the machinist, and, in some cases, the blocks were flawed so that in a gross exaggeration, the bottom plate might have gone up like this. You can see as the load increases, the effect of this defect is ironed out. You can see the time increase. You give me a golden opportunity of which I want to take advantage. Someone pointed out, "How can you be sure that what you are seeing isn't connected just with changes in the state of stress of the bottom block?" Dennis checked that by using several different materials, plexiglass was one, for the top affair, and one sees nothing like that behavior.

PROF. JAMES KRUMHANSL (Cornell University): In recent years there have been substantial developments in the theory of propagation in irregular media, random media. Has the surface wave problem with randomness on the surface been done? I'm just fascinated.

DR. LEE: There's a gentleman who is going to give a paper on the dispersion of surface waves with variations in parameters below it. Is he here and would he care to comment on that? I don't know the answer to your question.

DR. THOMAS SZABO (Air Force, Cambridge Research Lab): I think there have been several papers, but I din't know that there were any experiments to verify it because it is a real problem.

PROF. KRUMHANSL: That's really this effect.

DR. LEE: Yes, I think so. I would like to talk with you about it.

PROF. GORDON KINO (Stanford University): People have done the analysis of grooves on surface waves and multigrooves in a random distribution of grooves. A guy in Australia started all this stuff. I can't remember his name right offhand, and there's a group at Lincoln Labs who have dome some very detailed theory in relation to this.

DR. LEE: Thank you, sir.

MR. STEVE HART: I think also there is a point that might be made and that is I think the particle displacement has to be essentially normal to the surface. You're not talking surface waves all the time. There's no question of those load wave types of motion.

DR. LEE: That's correct. I think that's really two questions. The displacement field of this solution is essentially perpendicular to the surface, to the interface, although there is a component parallel to the interface in both cases, and I don't think there are any long waves, things involving the whole substrates.

MR. HART: Well, I guess what I was thinking was you get no leakage from a motion which is parallel to the surface. So, it pretty much says that you have to have in this kind of situation, a normal displacement. I've done this experiment with a leaky wave around the cylinder with a hole in it. If you polarize your incident shear wave parallel to the surface generators, you get no leakage. But if you go to normal polarization, then you get, as I think somebody else pointed out--

DR. LEE: I think that's a somewhat different effect than the one going along the plane surfaces.

MR. HART: Yes, I think it is.